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Interference-free superposition of nonzero order light modes: Functionalized optical landscapes

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In this paper, we utilize the incoherent superposition of nonzero order light modes. We show that this approach brings an additional degree of freedom to the generation of optical fields and notably the formation of superpositions that are otherwise unattainable through the use of refractive or diffractive optical elements and coherent or incoherent light sources. We employ this technique in two exemplary cases: first to create a field with tunable orbital angular momentum whose spatial intensity distribution remains unchanged and second to form an unusual type of "nondiffracting" light beam. © *2011 American Institute of Physics*. [doi:10.1063/1.3552202]

While the fundamental zero-order Gaussian mode remains central to the vast majority of applications in photonics, the rapid evolution of a broad range of photonics disciplines has witnessed the introduction of many different nonzero order beam types which are exploited for their special and often unique characteristics.

The concept of propagation invariant ("nondiffracting") light modes was proposed and experimentally realized by Durnin and co-workers[1,2] in 1987. They introduced the zero-order Bessel beam (BB), featuring a high intensity nonspreading central core and an ability to self-heal during propagation.[3] To date, this concept has been extended to higher-order BBs (HOBBs),[4] as well as other beam families such as Mathieu, Airy, and parabolic beams, the later two may propagate along curved trajectories.[5] In 1992, Allen and colleagues found that Laguerre–Gaussian (LG) beams with an azimuthal phase term carry orbital angular momentum[6] (OAM) and in 1995, a LG beam was employed in the initial demonstration of OAM transfer between light and matter.[7]

However, the special features of such modes directly dictate their intensity distribution. Using coherent fields, it is not possible to alter OAM or to extend or reduce the extent of any nondiffracting regions without influencing the field intensity distribution and vice versa (e.g., Ref. 8). For example, if one attempts to alter OAM by coherent superposition of two LG modes with mutually opposite azimuthal index, then the intensity will no longer possess the characteristic azimuthally independent annular shape of the individual modes.[9,10] Similarly, trying to alter the intensity distribution of a BB by superimposing several coherent Bessel modes of different order or propagation constant will result in a field that cannot propagate in a "diffraction-free" manner.[11]

Avoiding these unwanted interference effects by suppressing the spatial coherence of the modes would not resolve the issue. While it would be possible to reconstruct the intensity profile of the modes along a single lateral plane using spatially incoherent light, the special characteristics of the modes are inherently linked with their spatial coherence, which naturally yield an invariable phase relation between every pair of spatially displaced points. If coherence is lost, the azimuthal phase-gradients responsible for the OAM of the LG field will vanish and, for the case of BBs, the characteristic spreading of the mutually incoherent parts will no longer permit nondiffracting propagation.

However, if an individual mode remains coherent with itself but mutually incoherent with all others, then the unwanted interference effects are eliminated. Thus, any composition of coaxial nondiffracting beams will remain nondiffracting. Additionally, the intensity of the modes is represented simply by the sum of the individual mode contributions. The same argument may be made for the total OAM for the case of LG modes.

In this paper, we experimentally generate such compositions and show that this principle can be exploited in a number of practical applications. In our implementation, individual modes are generated by digital holography and their incoherent superposition is realized by time-sharing between the individual modes; only a single coherent mode of the chosen series exists at any one time and individual modes are rapidly and periodically exposed. If the system response is slow in comparison with the switching rate, then this is equivalent to the simultaneous spatial coexistence of multiple mutually incoherent modes.

We introduce the system and demonstrate the interference-free multiplexing of single and multiple modes. Then we show two practical examples demonstrating the unique capabilities of the system. In the first, we demonstrate smooth tuning of the OAM of a field with noninteger multiples of $\hbar$ per photon (statistically averaged) while keeping the intensity distribution unchanged. We exploit this field for controllable bilateral rotation of microparticles within an optical trapping system.[12] In the second example, the generation of an "inverted Bessel beam" is shown; this nondiffracting field is the direct opposite of a zero-order BB, having instead a "nondiffracting" central core of darkness surrounded by an extended high intensity region.

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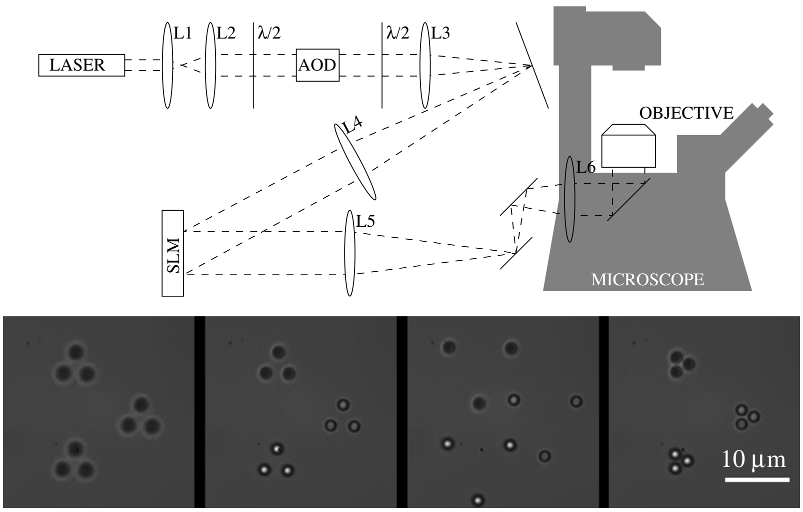

FIG. 1. The tandem system of SLM and AOD used for our experiments. The camera image insets show multiple optical traps using tightly focused Gaussian modes. Similar optical trapping system was introduced by Akselrod *et al.*[14]

The experimental system is shown in Fig. 1. The optical trapping system produces the resulting fields within a microscopic sample chamber and the mechanical influence of the fields are tested by observing the dynamics of polystyrene particles (1 μm in diameter) immersed in a water medium as seen in camera image insets of Fig. 1. En route to the sample, the laser beam [IPG, 1064 nm (IPG Photonics (UK) Ltd, London, United Kingdom)] encounters two adaptive optical elements: an acousto-optical deflector (AOD) and a spatial light modulator (SLM). Both elements are placed at planes conjugated to the back aperture of the microscope objective [Olympus UPlanSapo 60×1.2 W (Olympus UK Ltd, Essex, United Kingdom)] The AOD [IntraAction, DTD-274HD6M (IntraAction Corp, Bellwood, Illinois)] is capable of rapid beam-steering at rates of tens of kilohertz, while the SLM [Hamamatsu X10468-3 (Hamamatsu Photonics UK Ltd, Hertfordshire, United Kingdom)] can imprint any phase distribution to the reflected beam and thus create any arbitrary light mode and position it in a given volume. Utilizing our previously reported optimization algorithm,[13] the SLM corrects the optical aberrations of the entire system, maximizing efficiency. All modes are produced simultaneously and spatially displaced by the SLM, such that their mutual separation exceeds the dimension of a designated area (field of view). Individual modes are then distributed within this area by the AOD. A similar system employing purely Gaussian modes was previously exploited to generate a powerful multiple optical trapping system[14] where optical trapping sites are multiplexed by both devices combining the advantages of both approaches.

The generation of multiple time-shared zero-order BB is shown in Fig. 2. A single BB is generated using spatial filtration at the SLM plane[15,16] [Fig. 2(a)] and multiplexed by the AOD into the complex pattern shown in Figs. 2(b) and 2(c). Arbitrary multiplexing of different modes is presented in Figs. 2(d)–2(f); a combination of Gaussian and LG beams is created by the SLM and each of these modes have been multiplexed by AOD into the desired patterns. In principle, it is possible to create and pattern any number of modes in this way, given sufficient laser power. As Figs. 2(b), 2(c), and 2(f) clearly demonstrate, time-sharing has ensured that no unwanted interference effects are produced.

LG beams may have an on-axis vortex and produce optical torques that can rotate trapped particles via transfer of their inherent OAM.[7] The rotation rate of the trapped particle is a function of laser power, wavelength, and the azimuthal index "l" of the vortex beam.[17] "Classic" vortex beams, with integer values of l, therefore produce quantized values for OAM transfer and lead to smooth rotation around the beam annulus. Previously reported experiments to impart noninteger amounts of OAM to trapped particles using fractional vortex beams[9] or interference of two classic vortices[10] produce azimuthal intensity variations that inhibit smooth particle motion unless the particles are of sufficiently large diameter to bridge any azimuthal gaps in intensity. In contrast, the interference-free superposition we present can be used to produce smoothly varying OAM transfer without the limitation of such intensity minima.

In our system, a pair of vortices of opposite topological charge is created by the SLM; each pair is consequently multiplexed into two by the AOD and positioned such that one vortex of each type is overlapped [central ring, Figs. 3(c) and 3(d)]. The net OAM of the overlapped vortex is the superposition of the OAM of the two individual vortices. Since the overlapping vortices are time-shared, the net effect is the addition of their intensities, with no interference involved. The imperfections of intensity uniformity along the beam circumference seen in Fig. 3(c) are mostly caused by the presence of the AOD in the system. In our study, we used polystyrene particles (1 μm in diameter) which have very low absorption. Thus the particles gain OAM predominantly via scattering of the beam whose helical wave fronts give

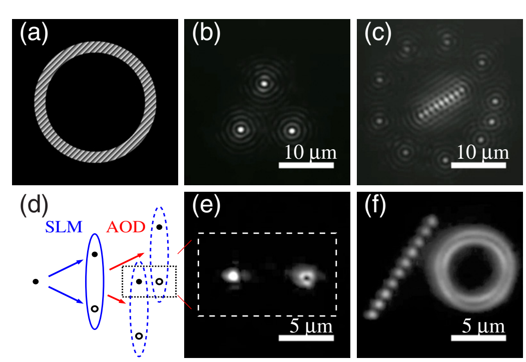

FIG. 2. (Color online) (a) A single BB is created by spatial filtration at the SLM and [(b) and (c)] multiplexed by the AOD without producing interference. The combination of the SLM and AOD can create different beam modes which can be multiplexed and manipulated independently [shown schematically in (d) and experimentally in (e) and (f)].

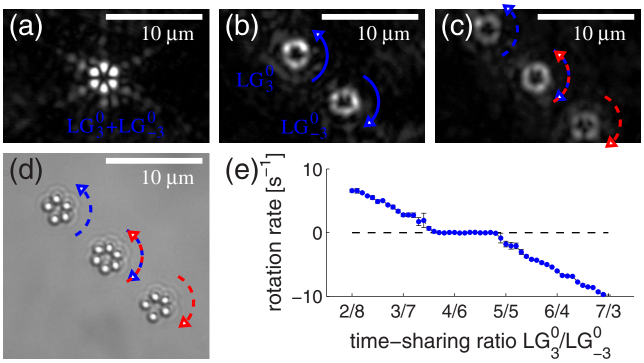

FIG. 3. (Color online) (a) The interference pattern of two vortex beams of opposite topological charge. (b) A pair of oppositely charged vortex beams created by the SLM. (c) The AOD multiplexes the original two beams to produce four; one of each type is overlapped by the AOD. (d) Particles trapped in the individual and combined vortices experience different torque forces and rotation speeds. (e) OAM transfer in the central trap as a function of the power ratio between the time-shared vortices.

rise to an azimuthal component of the scattering force.

Figure 3(e) demonstrates the net angular momentum transfer from the resultant vortex superposition as a function of the ratio between the contributions of the individual vortices. The influence of intensity modulation on trapped particle dynamics has been extensively studied in the past decade.[18] In comparison with purely holographic optical tweezers, our approach offers a means to minimize these effects, which in our case are only present due to imperfections in the intensity distribution. The effect of these imperfections is seen in the zero velocity plateau in Fig. 3(e), which occurs when the time-shared ratio of the contributing beams approaches unity and the net force of the OAM transfer to the particles is therefore at its weakest. In addition, the retarding force of static mechanical friction, created as the particles are pushed toward the top cover slip, is also more significant when the net OAM transfer is small.

Interference-free superposition of an extended series of modes can also be used to generate previously experimentally unrealizable beams. As a demonstration of this capability, we present an intriguing variation of the popular BB, the "inverse" BB, which has a nondiffracting dark core surrounded by a high intensity field. Described by the following expression, an inverse BB can be generated by a superposition of mutually incoherent HOBBs (Ref. 19):

$$1-[J_0(x)]^2 = 2\sum_{k=1}^{\infty}[J_k(x)]^2. \tag{1}$$

Figure 4 demonstrates the experimental production of an inverse BB. The SLM produces an array of HOBB beams which are multiplexed and combined in the center position by the AOD. The low intensity nondiffracting central core makes the inverse BB an eminent candidate for efficient guiding of low-index particles since they will be attracted into the central core from large radial distances. In contrast, a HOBB would repel the particles away from the beam axis unless they are directly located within the central core region. An additional benefit of the inverse BB is that high-index particles would experience repulsion from the axis across the whole lateral cross-section of the beam, thus making it an ideal solution for aerosol particle clearing applications.[20]

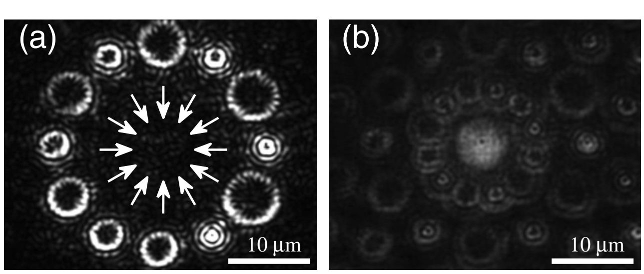

FIG. 4. (a) HOBB modes are created by the SLM, (b) then multiplexed and combined in the center by the AOD to create the time-shared noninterfering superposition of these modes; the inverse BB.

In this paper, we have shown that the interference-free superposition of nonzero order laser modes is a powerful technique for generation and manipulation of optical landscapes that are not available in other geometries. With this approach, it is possible to create intriguing superpositions of laser modes without the limitation of unwanted interference effects. We demonstrated how to apply this technique to yield unrestricted control of OAM in an optical field and presented generation of an innovative nondiffracting beam. We have illustrated this with selected examples; however, this technique can be utilized in a variety of applications, where the interaction between propagating coherent modes is a limiting factor for the functionality of the resulting optical landscape.

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